Characterisation, mechanical and microstructural behaviour of an unsaturated silt

G. McCloskey & M. Sánchez
Department of Civil Engineering, University of Strathclyde, Glasgow, UK

E. Romero
Department of Geotechnical Engineering, Universitat Politècnica de Catalunya (UPC), Barcelona, Spain

ABSTRACT: This study investigates an unsaturated silt sampled from an embankment along the Bengawan Solo River in East Java, Indonesia. Load and soak oedometer tests were carried out on laboratory compacted samples and on undisturbed samples. For samples compacted dry of optimum at low dry densities, significant settlements were observed on wetting, with a maximum collapse potential of 14% evaluated. A qualitative investigation of the microstructure of the material was carried out using an Environmental Scanning Electron Microscope. Micrographs were taken of the material under the following conditions: (a) Compacted, (b) Compacted, Loaded, (c) Compacted, Loaded & Soaked, and (d) Undisturbed. The ESEM images suggest that the fabric of the Undisturbed sample and the Compacted, Loaded & Soaked sample are similar. These results appear to indicate that the undisturbed material sampled at the end of the wet season has already undergone the process of plastic collapse compression in-situ.

1 INTRODUCTION

Many unsaturated soils may undergo a significant settlement when wetted under load. If water is readily available then this settlement can occur rapidly; this is known as plastic collapse compression. Lawton *et al.* (1992) define wetting-induced collapse as the densification of a soil caused by the addition of water at a constant total vertical stress. The term 'collapse' is used in the rest of this text to identify this irreversible hydro-mechanical phenomenon.

There are four main conditions required for collapse to occur (Barden *et al.* 1973, Mitchell 1976): (i) an open partly unstable, partly saturated fabric; (ii) high enough total stress that causes the structure to be metastable; (iii) a binding or cementing agent (including the effect of water menisci), which stabilises the structure when dry and (iv) addition of water. Each of these must be present to produce a collapse phenomenon, the degree to which each is present influences the resulting collapse observed.

A common observation during load and soak tests is that samples collapse from their initial water content loading curve to the saturated compression line (Holtz & Hilf, 1961). The amount of collapse which occurs depends on the applied stress level. At low stress levels a small amount of expansion or compression may occur. Under these conditions the potential for collapse increases with increasing vertical stress, at least in the range where the loading/collapse yield locus (BBM model, Alonso *et al.* 1990) is activated on wetting. However experimental observations have also indicated that at higher stress levels collapse potentials may reduce, resulting in the determination of a maximum collapse, (Balmaceda, 1991; Futai, 1997; Rao & Revanasiddappa, 2006). This reduction in collapse potential at higher stress levels may be attributed to a greater compression of the sample, which results in a higher dry density of the sample and a higher degree of saturation of the sample (Lawton *et al.*, 1992). Both of these factors reduce the potential for collapse. Eventually at higher stresses the soaking process induces no collapse.

In early Scanning Electron Microscopy (SEM) studies Barden et al. (1973) and Collins & McGown (1974) investigated the arrangements present within the microstructure of natural soils. Barden et al. (1973) in particular were interested in investigating the arrangements which existed within a number of sands, loessial soils and clays which exhibited collapse. Jommi & Sciotti (2003) studied differences in the microstructure of laboratory compacted and field compacted material using SEM. The study raised questions over whether soil compacted in the laboratory should be used as a reliable reference material for field compaction given the resulting differences in microstructure.

With the shift towards the use of Environmental Scanning Electron Microscopy (ESEM), in which the sample can be imaged in its natural wet condition, authors are again turning their attention to microstructural changes which occur along hydraulic paths. Villar & Lloret (2001) observed the swelling behaviour of compacted FEBEX bentonite under constant volume, in which macropores became filled with the swelling bentonite particles. Zhang *et al.* (2005) investigated changes in the microstructure of a double porosity tropical soil along drying and wetting paths.

This paper presents the characterisation of the Bengawan Solo fill, a silt used in flood embankment construction in Indonesia. At the site under investigation, a number of engineering works have been constructed to improve the stability of the embankments. However it appears that these works provide the loading required, alongside the readily available access to water, low densities and moisture contents dry-of-optimum to produce conditions favouring collapse. The mechanical behaviour of this fill is presented in a number of soak and load oedometer tests on samples at (i) peak dry density (i.e. BS Light Compaction), (ii) low dry density and dry of optimum and (iii) undisturbed samples. Furthermore the vertical stress at which maximum collapse occurs is determined. The microstructure of the Bengawan Solo fill is investigated using ESEM under a number of different conditions, (a) Compacted, (b) Compacted, Loaded and (iii) Compacted, Loaded & Soaked, in order to determine the microstructural changes which are responsible for collapse induced volume changes. For comparison an undisturbed sample was also investigated using ESEM.

2 SITE DESCRIPTION

The soil investigated here was sampled from a site located along the flood defence embankments of the Bengawan Solo River, in the village of Kedunhardjo, East Java, Indonesia. At the site the river is 100m wide and the embankment is 10m high and is frequently overtopped during the wet season.

During the site investigation low dry densities ranging from 1.18 -1.36Mg/m^3 were determined alongside high moisture contents ranging from 36-43%. The site investigation was carried out at the end of the wet season. Shear vane tests were also carried out and the cohesion ranged from 20-40kPa, indicating a soft soil as classified in BS: 8004:1986.

There is a recurrent history of failure of the flood defence embankments at the site which is discussed in greater detail in McCloskey *et al.* (2008). Figure 1 shows a global failure, in a gabion reinforced section of the embankment. Other remediation measures put in place by the Ministry of Public Works include concrete slabs to protect erosion. McCloskey et al. (2008) argued that these measures provided the necessary loading, alongside the low in-situ densities and readily available access to water to create conditions favouring plastic collapse compression of the fill material. This phenomenon may be one of the possible mechanisms which contributed to the global failure of the gabion reinforced embankment (Fig. 1).

3 SOIL CHARACTERISATION

The soil investigated within this study is a medium plasticity sandy silt (Fig. 2) with particle density ρ_s=2.72Mg/m^3. The soil can be classified as an inorganic silt of high compressibility (MH) in the Unified Soil Classification System (LL=53%, PL=37%, I_p=16%). Although the soil has a small clay fraction, it has an activity A = 0.94, due to the high percentage of smectites in the clay fraction (88%), which have A=1-7 (Mitchell, 1976). Kaolinite makes up the remaining minerals in the clay fraction with an activity A = 0.5.

The British Standard Light Compaction curve (input energy per unit volume = 596kJ/m^3) is presented in Figure 3; under this compactive effort the soil has a maximum dry density of 1.47Mg/m^3 and an optimum moisture content of 28%. However Dr. Ria Soemitro of ITS, Surabaya, who works in collaboration with the Ministry of Public Works has communicated to the authors that the embankments were constructed at 80 to 85% of the maximum dry

Figure 1. Global failure along gabion reinforced embankment

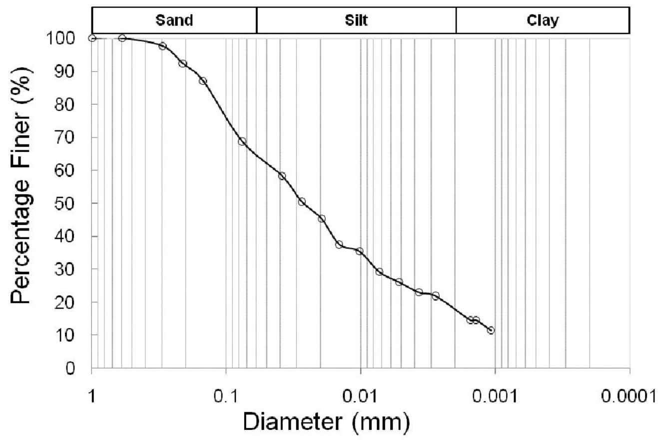


Figure 2. Grain Size Distribution Curve, Sand: 36%, Silt: 47%, Clay: 17%

dry density. This range is highlighted in Figure 3 and explains why low dry densities have been found at the site. It is for this reason that the samples prepared in the laboratory have been compacted to low dry densities in order to recreate conditions which are similar to those in the field.

In this study tests were conducted using both laboratory compacted and undisturbed samples. The undisturbed samples were retrieved from the embankment using box samples according to the guide lines given by Fookes, (1990). Box samples were preferred to U_{100} tubes in order to protect the microstructure of the material. This undisturbed material was sampled at the end of the wet season; one week after the embankments had been overtopped.

Figure 4 presents the water retention curve for both undisturbed and laboratory compacted samples. The undisturbed sample is wet of optimum and has a higher dry density than the laboratory compacted samples. The curves converge at low moisture content and high suction. It is important to note from the retention curve that at a moisture content of 20%, a low density laboratory compacted sample can have a suction of around 1MPa. A sample with a moisture content of 35% at the same density would have a suction of around 35kPa. As the material used to construct the embankments is transported material (taken from the riverbed) we can assume that there

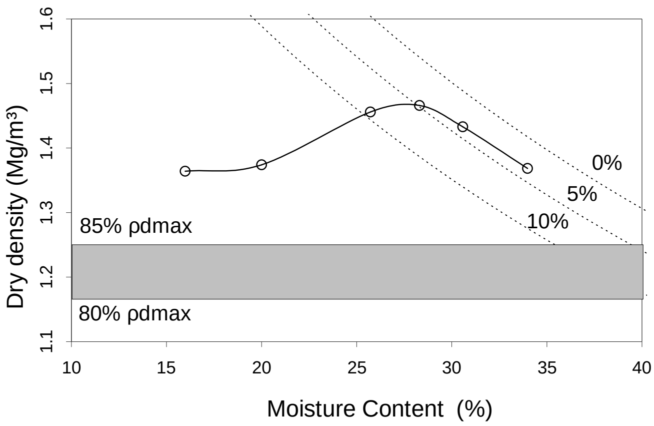


Figure 3. BS Light Compaction Curve, ρ_{dmax}: 1.47Mg/m^3, w_{opt}: 28%

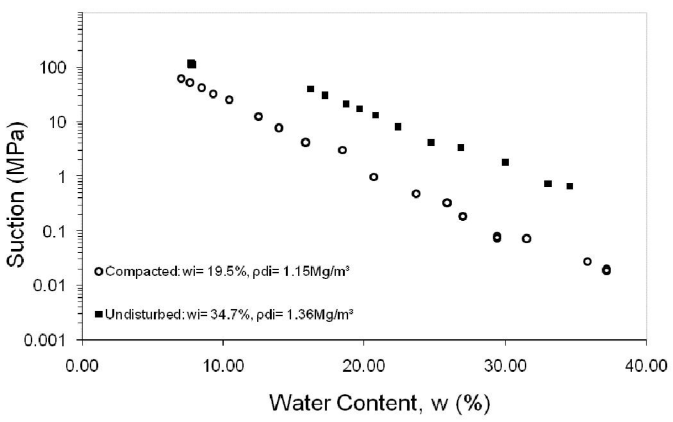


Figure 4. Water Retention Curves for laboratory compacted & undisturbed samples

remains no cementation effects within the soil and that the stabilising effect under dry of optimum conditions and at low dry densities is due to the role of suction.

4 MECHANICAL BEHAVIOUR

Three series of load and soak oedometer tests are presented here: (i) BS light compacted peak samples; (ii) Low density, dry of optimum compacted samples (prepared at low dry densities similar to those found in-situ); and (iii) Undisturbed samples.

In series (i) BS light compacted peak samples, the specimens were prepared from a BS Compaction mould in order to recreate as closely as possible the peak conditions. It was not possible to recreate the dry of optimum samples, series (ii), in the compaction mould due to the crumbly fragile nature of the soil in this condition. The low density laboratory compacted samples were prepared in retaining rings 60mm in diameter, 18mm high in 3 layers using the damp tamping method. The undisturbed specimens were prepared from the box samples by cutting out block samples and trimming around the cutting rings.

No collapse was observed in series (i) BS light compacted peak samples on wetting at 127kPa, (Fig. 5). This is to be expected at the optimum condition.

Figure 6 presents the results from soak and load oedometer tests on remoulded samples with similar densities to those found in-situ. It can be clearly seen that the samples collapse from their natural water content loading curve to the saturated compression line, (Holtz & Hilf, 1961). Also noticeable is that at low vertical stresses the amount of collapse increases and at higher stresses it reduces. This is further highlighted in Figure 7 where the collapse potential (%) is plotted for the settlement due to wetting under each vertical stress. It is clear that the maximum collapse of 14% occurred on wetting at a vertical stress of 127kPa. Fookes (1990) published

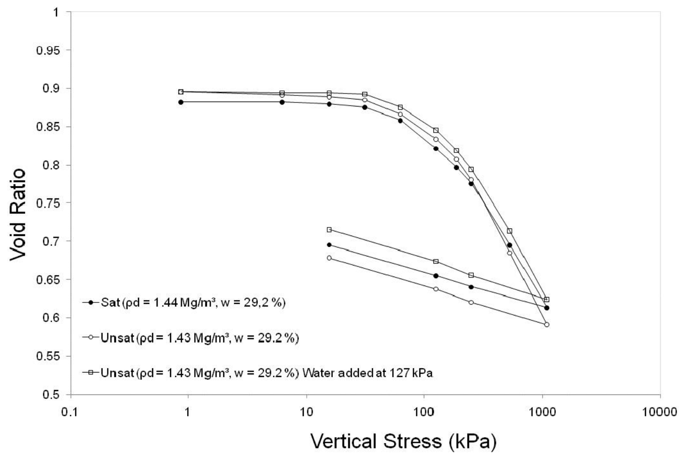


Figure 5. Oedometer Results: Series (i) BS light compacted peak samples

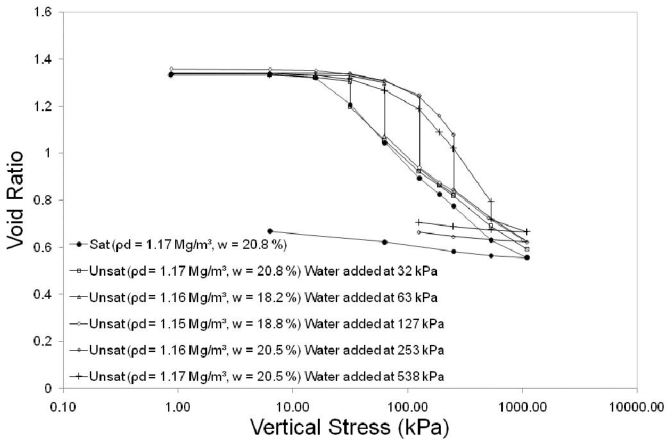


Figure 6. Oedometer Results: Series (ii) Low density, dry of optimum samples

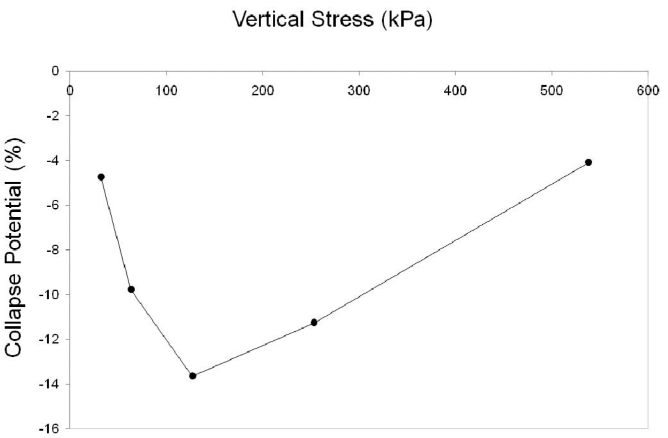


Figure 7. Collapse potentials at different vertical stresses for Series (ii) Low density, dry of optimum samples

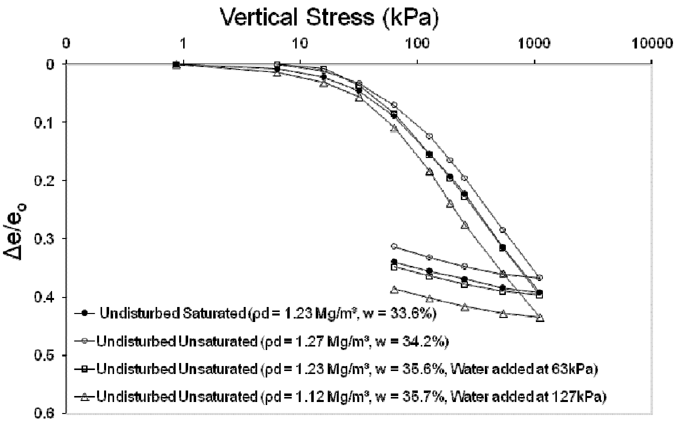


Figure 8. Oedometer Results: Series (iii) Undisturbed samples

guidance relating collapse potential to severity of problem and suggested that values of collapse potential between 10 and 20 % resulted in 'severe trouble' problems.

The results from soak and load tests on undisturbed samples are presented in Figure 8. Specimens retrieved from the box samples varied greatly in dry density as a result of the heterogeneity of the material on site. Therefore these results have been plotted in terms of normalised void ratio. No immediate settlements were observed on wetting at loads of 63kPa and 127kPa. It is important to note here that the sample which was loaded to 127kPa and then inundated had a low dry density of 1.12Mg/m^3, lower than the densities of the laboratory compacted samples in series (ii) and yet no collapse was observed. This highlights the importance of the role of the initial moisture content in producing collapse as suggested by Lawton *et al.* (1992).

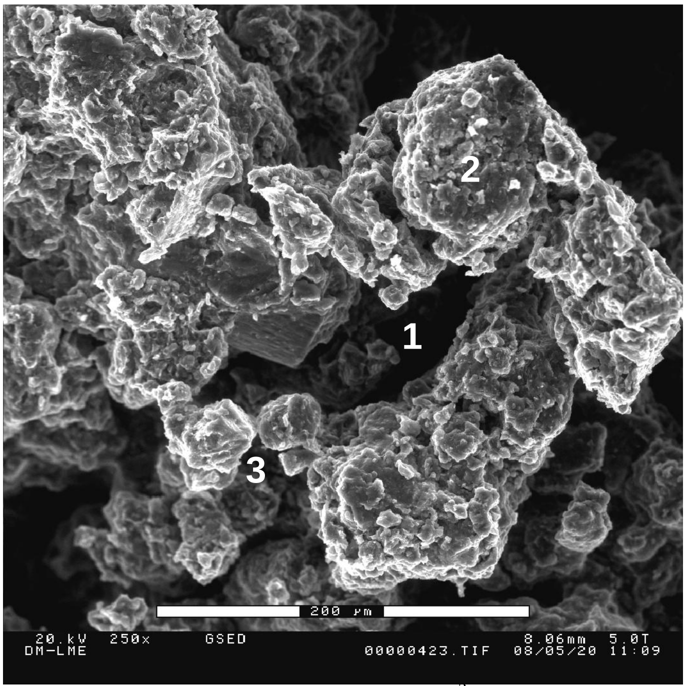
The oedometer results indicate that the Bengawan Solo fill material is a collapsible material when compacted to low dry densities and at dry of optimum moisture content. Significant collapse induced volume changes were observed for samples at low dry densities in the range of dry density to which the embankments were constructed. Samples prepared at optimum dry density and moisture content showed no collapse on wetting. Undisturbed samples, wet of optimum showed no collapse even at low dry densities.

5 MICROSTRUCTURAL STUDY

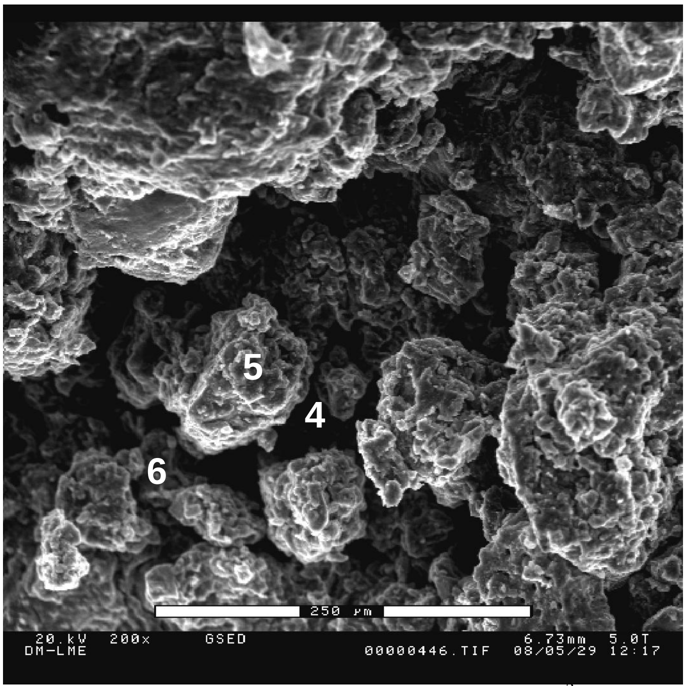
A qualitative microstructural study was carried out using environmental scanning electron microscopy (ESEM) to investigate the evolution of microstructure during the collapse process. In this study three samples of the same initial conditions (w~19.5%, ρ_d=1.15Mg/m^3) were investigated at three different stages of the collapse process: (a) Compacted, (b) Compacted Loaded and (c) Compacted, Loaded & Soaked. These images were then compared to that of an undisturbed sample. ESEM unlike conventional SEM allows samples to be imaged under wet conditions and also requires no special coating prior to imaging; thus simplifying the specimen preparation procedure greatly. The specimens imaged here were carefully fractured from larger samples in order to obtain representative natural surfaces.

Figure 9a presents an image of the compacted sample, which shows an open structure with large macropores (1), surrounded by defined aggregates (2) which are connected via bridges (3). It is difficult to discern sand and silt grain particles as it appears that everything is clothed with clay particles forming aggregations. Moving to the Compacted, Loaded sample in Figure 9b, there are still macropores (4), defined aggregations (5) and bridging connections present (6). Figure 9c shows the compacted sample after loading and soaking, (i.e. after collapse). There is a marked absence of large macropores within this sample. It is still possible to determine where aggregations existed prior to wetting (7), however as a result of the flooding, the fabric has become fused due to a softening of the aggregations and the fabric as a whole has become more uniform. The soaking process (which accounts for the difference in the samples in Fig. 9b and Fig. 9c) has resulted in the removal of meniscus water lenses, as the voids became increasingly filled with bulk water during flooding. It is these meniscus water lenses present at the contacts which provide a stabilising effect (through an additional component of normal force, Fisher, 1926) in the dry, low density compacted sample (1MPa of suction). During wetting these lenses are removed and this additional force is lost. The overall change in fabric viewed in Figure 9c can be attributed to (i) the loss of rigidity of the aggregations, (ii) the loss of strength on wetting between contacts and (iii) the loss of strength of bridging material. These changes all result in the loss of the macropores which are absent in Figure 9c. It is the loss of these inter-aggregate macropores on wetting which causes the collapse induced volume changes observed in Figure 6. Similarly Barden *et al.* (1973) found that the collapse mechanism of clayey soils was due to an effective aggregated macrostructure rather than the rearrangement of flocculated clay particles on wetting.

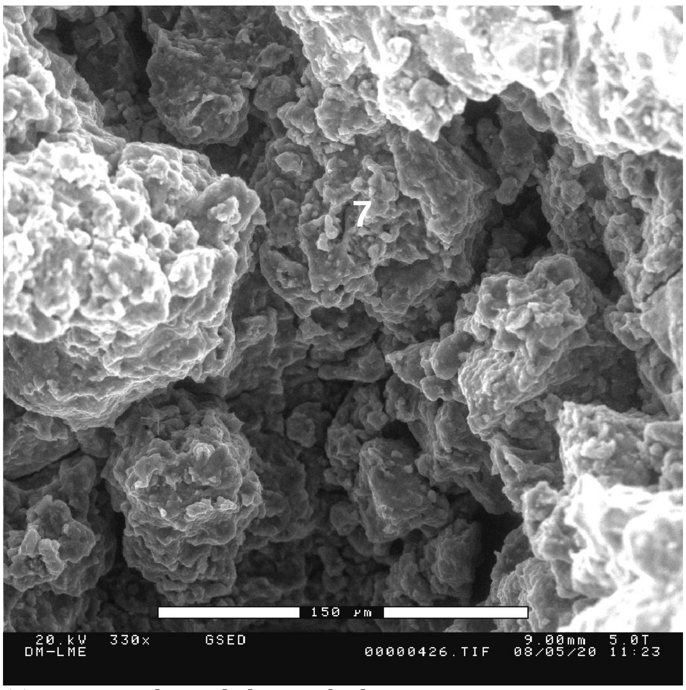
Finally the microstructure of an undisturbed sample was also investigated using ESEM. There are distinct similarities between the Undisturbed sample (Fig. 9d) and the Compacted, Loaded & Soaked sample in Fig. 9c), namely both show fused aggrega-



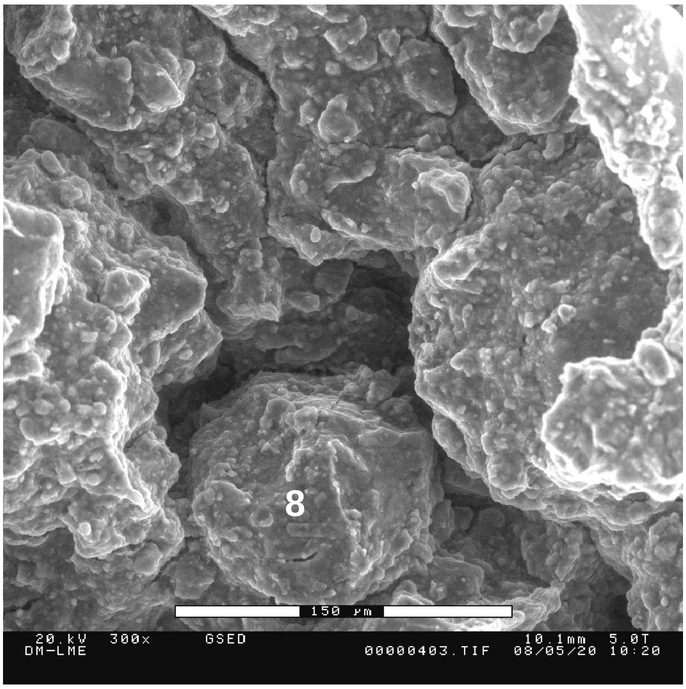
(a) Compacted: w =19.5%, ρ_d = 1.15Mg/m^3, e = 1.38



(b) Compacted, Loaded: w =19.0%, ρ_d = 1.19Mg/m^3, e = 1.29, Loaded to 127kPa for 24hrs



(c) Compacted, Loaded & Soaked: w = 27.7%, ρ_d = 1.40, e = 0.95



(d) Undisturbed: w = 30.5%, ρ_d = 1.34, e = 1.03

Figure 9. ESEM micrographs of (a) Compacted, (b) Compacted, Loaded, (c) Compacted, Loaded & Soaked and (d) Undisturbed samples

tions (7, 8) in a uniform fabric, with a marked absence of macropores. The outer covering of the fabric in the undisturbed sample appears to be more rounded than that in (Fig. 9c), this may be explained by the higher moisture content of the undisturbed sample. The comparison of Figures 9c and 9d suggests that the microstructure of the undisturbed sample is very similar to that of the Compacted, Loaded & Soaked sample (collapsed) created in the laboratory with initial conditions, dry of optimum at low dry density.

The qualitative microstructure investigation presented here highlights the changes which occur during the process of collapse. In particular the main microstructural changes noted were (i) the softening of aggregations; (ii) the removal of meniscus water lenses at contacts and (iii) the loss of strength of the bridging material on wetting. It is these changes which are responsible for the loss of the inter-aggregate macropores. The sample which underwent collapse in the laboratory showed a very similar microstructure to the undisturbed sample, which was sampled from the site at the end of the wet season. It appears from this investigation that the undisturbed material has already undergone collapse in-situ under its own self weight.

6 CONCLUSIONS

A characterisation of the Bengawan Solo fill material used to construct flood embankments in Indonesia has been presented herein. It has been reported that the material is compacted in-situ at dry densities of 80-85% peak dry density. A series of load and soak oedometer tests performed on specimens within this range exhibited collapse behaviour at a number of different vertical stresses (from 63kPa to 538kPa). Maximum collapse was found to occur at 127kPa.

The microstructure of this material was investigated with specific reference to the changes occurring within the soil during the collapse process. The wetting resulted in the softening of aggregations, removal of meniscus water lenses and loss of strength of bridging material to form a fused uniform fabric with no macropores. It appears from this qualitative study that the undisturbed material investigated has already undergone collapse in-situ under its own self weight. It is proposed that these results will be further investigated using mercury intrusion porosimetry to quantify the pore size distribution of these samples.

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